DOI: 10.13009/EUCASS2023-458
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Just-in-time Collision Avoidance (JCA) using swarms of nanosatellites (nanotugs)

Y. Ben Hamou[1], M. Colucci[2], G. Di Dio[3], M. Tommasi[2]

[1]IPSA - Ecole d'ingénieurs Aéronautique et Spatiale Paris, 63 Bd de Brandebourg Bis, 94200 Ivry-sur-Seine
[2]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino [3]Università degli Studi di Roma La Sapienza, Piazzale Aldo Moro 5, 00185 Roma

yoann.ben-hamou@ipsa.fr, s295757@studenti.polito.it, didio.1791757@studenti.uniroma1.it, s301850@studenti.polito.it

Abstract

This paper develops a new approach based on the JCA method, to avoid collisions between space debris using an ”octopus”. An ”octopus” is a complete system that clings to debris with its ”head” and four deployable "legs", each equipped with thrusters at the end. Firstly, a Zenit-2 upper stage and its trajectory have been identified to determine the injection orbit, the rendezvous and the avoidance maneuvers. Then, the amount of propellant to ensure the mission has been determined. Meanwhile, the structure of the "octopus" has been designed as well as the attachment to the debris. Finally, electrical, thermal, communication, sub-systems, cost and mass budgets have been documented.

1 Introduction

Since 1957, space activity has generated a huge number of objects in orbit. In 2022, around 36000 large objects of more than 10 cm have been catalogued, together with more than 1 million of debris larger than 1 cm and 150 million of debris major than 1 mm [1].
However, this high number of space debris can affect the success of future missions and space sustainability by increasing casualty risk on the ground following uncontrolled re-entry, damage of operational satellites, or generation of a large number of new debris following massive collisions.

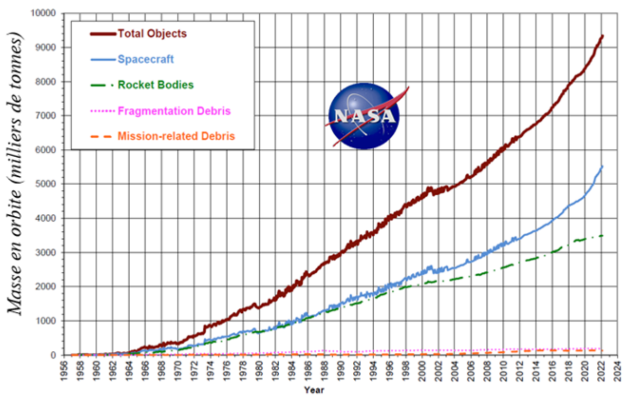

Figure 1: Evolution of the orbiting mass divided into categories [1]

For all these reasons, it appears necessary to find solutions to avoid such collisions and feed the so-called Kessler syndrome: when a collision occurs, a junk cloud is generated and spread in all directions.
To actively perform remediation actions, different solutions are now studied like Just-in-time Collision Avoidance (JCA) whose aim is to avoid a collision between two debris by modifying their orbital parameters. A small velocity variation ΔV is applied on one debris and result in an increase in the miss distance at the conjunction point.
Three main options have been developed for JCA whose "Just-in-time collision avoidance" (JCA) using ”Nano-Tugs”.

DOI: 10.13009/EUCASS2023-458

The general principle is to attach a suitable number of nanosatellites on a large potentially hazardous debris and modify its trajectory by using the propulsion system of the Nano-Tugs:

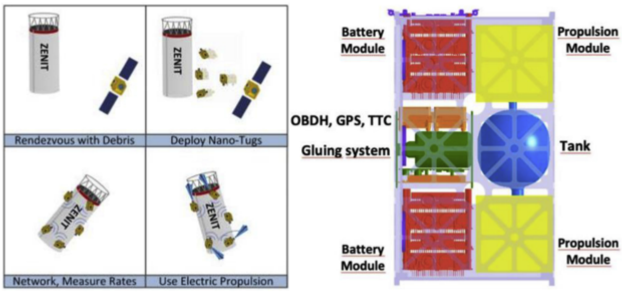

Figure 2: Schematization of the mission of the Nano-Tugs and their internal composition [4]

This solution is the foundation of this study. As work progresses, the alternative configuration has been provided with the concept of the "Octopus" to simplify the needs of the mission. The "Octopus" is a unique Nanosat that is able to attach to a derelict and act on it in order to avoid a potential collision. To substitute the propulsion capability of a group of Nanotugs, we implemented the structure of four deployable "legs" that deploy and stay in their fully extended configuration. The presence of thrusters at the end of each leg will give the possibility to perform the anticollision maneuver without the need for coordination between separate structures.

2 High Level Requirements

High Level Requirements have been classified into two sub-groups: Primary requirements given by the mission and Secondary requirements given by our expectations.

2.1 Primary requirements

- Target selection: The upper stage of the Zenit-2 launcher in Low Earth Orbit is used as the reference debris across this study. The debris is cylindrical with a structural mass of m = 9 *tons*, a radius R = 2 *m* and L = 10 *m* long. Its initial tumbling movement is assumed to be transverse at $\dot{\theta} \leq 2° s^{-1} = 3.5\ rad\ s^{-1}$.

- Parameters of the reference orbit (or debris orbit):

Orbit Inclination (degrees)	Apogee-Perigee (km)	Period (s)	Right Ascension of Ascending Node (degrees)	Eccentricity	Argument of Perigee (degrees)	Mean Anomaly (degrees)	Mean Motion (revolutions/day)	Revolution Number at Epoch
71.0062	849-835	6105.95	269.0576	0.009403	15.9125	344.2291	14.15013092528751	//

- Injection to orbit: A dedicated launch is used to reach the injection orbit in Low Earth Orbit (altitude of 860 *km* and inclination of 71°).

- Mission duration: The satellite will operate for at least 10 years, avoiding one collision per year (hypothesis coming from CNES).

- Cost: The overall cost of the mission should range between 100,000 € and 300,000 € for one CubeSat.

- Propulsion and propellant: Sufficient reserves of propellant must be provided to carry out one avoidance maneuver every year for 10 years using thrusters in the Octopus legs. The propellant mass margin is 20 % with 10 years of chemical stability for the propellant.

2.2 Secondary requirements

- Rendezvous with the debris: The rendezvous maneuver starts one kilometre behind the position of the debris with a series of hopping maneuvers to bring the octopus closer to the debris. The last meters are made with a continuous thrust maneuver that brings the octopus directly to the target with a very low velocity. The total duration of the rendezvous is equal to 30 days.

- Attachment: The octopus must be strongly attached to the debris without generating secondary debris.
- Mass of the spacecraft: The mass of the satellite should not exceed 25 kilograms.
- Avoidance maneuver: The avoidance maneuver should start 24 hours before the expected collision. The tumbling rate shall be reduced in less than 60 days once the satellite is attached to the debris.
- AOCS: Accuracy of AOCS is equal to 0.1 and $0.1s^{-1}$.

3 Trajectories

For the computations concerning this chapter, a circular orbit has been assumed with a semimajor axis equals to 7227 *km*, and an average altitude equals to 849 *km*.
For this mission, it is decided to do a dedicated launch which means that our mission has full authority of the rocket's payload and destination. To reach the desired orbit, a small launcher starting from CSG Kourou will be used considering the data from the injection accuracy table taken from the Vega-C launcher:

a Semimajor axis [km]	± 15
e Eccentricity	± 0.0012
i Inclination [deg]	± 0.15
Ω Right Ascension of the Ascending Node [deg]	± 2

Table 1: Injection errors [3].

3.1 Corrections

If we consider the orbit injection at 1 *km* below the target's orbit (848 *km*), it will take almost one year to correct the drift (345.4 *days*).
Therefore, the number of days in which we want to do the rendezvous are set to 30 *days* and we deduce the altitude difference at injection. With this computation, the injection orbit should be at 860 *km*, so 11 *km* above the target's orbit. Concerning the inclination, it is decided to do a correction maneuver combined with the Hohmann transfer in order to save fuel.

3.2 Phasing

For what concerns the phasing, it is needed to find the initial phase between the chaser and the target in order to reach the distance of 1 *km* from the target position after the Hohmann transfer. At the end of the Hohmann transfer, the spacecraft arrives at 1 *km* behind the target, which in degrees it is translated in:

$$\phi = \frac{1\ km}{2\pi r_{849}} \times 360 = 7.92 \times 10^{-3}\ deg \tag{1}$$

In order to arrive at this phase angle, the Hohmann transfer has to start when the phase angle between the two objects is as the following:

$$\phi_0 = \phi - (n_2 - n_1) \times T_H = -0.85\ deg \tag{2}$$

Where:

- n_2 is the angular velocity of the target
- n_1 is the angular velocity of the chaser
- T_H is the time of the Hohmann transfer

In conclusion, the octopus has to begin the Hohmann transfer when it is 0.85° from the target.

3.3 Hohmann Transfer

In order to reach the debris' orbit, the octopus needs to perform a Hohmann transfer.
In order to do that, it is necessary to apply a first impulse tangent to the orbit of the octopus, and a second lower impulse tangent to the final orbit. Considering that V_1 is the velocity of the outer orbit and V_2 is the velocity at the apogee of the Hohmann trajectory, it is possible to exploit a combined maneuver in order to reach the target's orbit and change the inclination at the same time, so that the first impulse is given by:

$$\Delta V_1 = \sqrt{V_1^2 + V_2^2 - 2 \times V_1 \times V_2 \times cos(0.15)} \tag{3}$$

The final ΔV will be:

$$\Delta V_{total} = \Delta V_1 + \Delta V_2 = 16.94 \ m \ s^{-1} \tag{4}$$

Where the inclination corrections have not been considered.

3.4 The Rendezvous-from the entry point to the debris

3.4.1 Hopping maneuver

First, it is decided to do a hopping maneuver along V-bar with radial thrust [4]. For this maneuver it is necessary to use the Hill-Clohessy-Wiltshire equations that will lead to the following formula of the ΔV

$$\Delta V_z = \frac{\Delta x \times n}{4} \tag{5}$$

Eventually, the following results are obtained:

- $\Delta V_{z,total} = 0.5108 \ m \ s^{-1}$
- $Distance\ from\ the\ target = 7.8125 \ m$
- $Number\ of\ hops = 7$

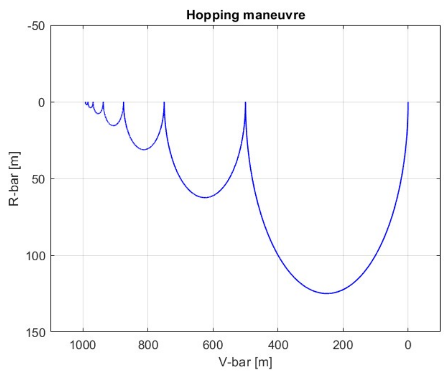

Figure 3: Hopping maneuver from the entry point to 7.8125 m of distance from the target

The figure 3 shows the relative motion of the octopus with respect to the debris. In fact, during this motion, the octopus remains co-orbiting with the target, requesting the ground to give it the go-ahead for the next phase.

DOI: 10.13009/EUCASS2023-458

3.4.2 Straight line approach with constant velocity along V-bar

After some time for monitoring, it is necessary to do the continuous thrust maneuver along V-bar in order to approach the debris. Once again, the Hill-Clohessy-Wiltshire equations are used. The ΔV needed in order to perform the continuous thrust maneuver is:

$$\Delta V_{continuous\ thrust} = \frac{\Delta x}{t_{maneuver}} \tag{6}$$

The $t_{maneuver}$ will be dictated by the tumbling rate of the debris and it will be perfectly controlled if the octopus has to perform the attachment to a tumbling body. If the body is not tumbling on the ideal axis for the maneuver (so that we cannot do an attachment maneuver with a straight-line approach along V-bar), the octopus needs to turn around the target in order to align along its principal rotation axis to perform the attachment.

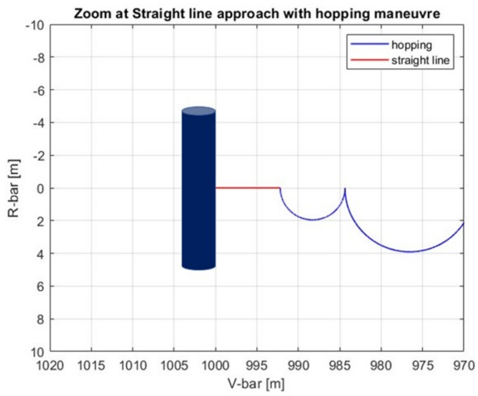

Figure 4: Zoom at the last steps for the rendezvous in the ideal case.

During the continuous thrust maneuver, the spacecraft will start moving accordingly to the tumbling of the target, until it will be able to perform the attachment.

3.5 Just in time collision avoidance maneuver

Now, we consider that the octopus has completed the attach maneuver and it is considered as a whole with the debris. To deviate the orbit, because of an approaching satellite in time, it is decided to perform the maneuver 24 hours before the expected collision, inducing a 1 km margin at the expected point of collision. In this way, when the satellite arrives at the debris' orbit, we will be already distant enough in order not to have any risk. The collision avoidance is done by a tangential thrust maneuver towards or against the direction of the velocity of the debris.

The Hill-Clohessy-Wiltshire equation with an LVLH reference frame will be considered again.

In order to obtain a drift motion, it is necessary to give an impulse in the V-bar direction ΔV_{x1}. From the previous paragraph it is possible to retrieve the boundary conditions:

$$At\ t = 0 : \begin{cases} x_0 = 0 \quad z_0 = 0 \\ \dot{x}_0 = \Delta V_{x1} \quad \dot{z}_0 = 0 \end{cases} \tag{7}$$

$$At\ t_f = 24\ h : \begin{cases} x_{t_f} = \Delta x = -1\ km \quad z_{t_f} = 0 \\ \dot{x}_{t_f} = 0 \quad \dot{z}_{t_f} = 0 \end{cases} \tag{8}$$

Considering these conditions, the HCW equations are:

DOI: 10.13009/EUCASS2023-458

$$\begin{cases} x_{t_f} &= \frac{4\Delta V_{x1}}{n} sin(nt_f) - 3\Delta V_{x1} t_f = \Delta x = -1 \\ z_{t_f} &= \frac{2\Delta V_{x1}}{n} cos(nt_f) - \frac{2\Delta V_{x1}}{n} = 0 \\ \dot{x}_{t_f} &= 4\Delta V_{x1} cos(nt_f) - 3\Delta V_{x1} = 0 \\ \dot{z}_{t_f} &= -2\Delta V_{x1} sin(nt_f) = 0 \end{cases} \tag{9}$$

The following result is obtained:

$$\Delta V_{x1} = \frac{-1}{\frac{4}{n} sin(nt_f) - 3t_f} = 3.9\ mm\ s^{-1} \tag{10}$$

So, in order to be at 1 km of distance along V-bar from the point of the expected collision, it is required to give an impulse of 4 $mm\ s^{-1}$.

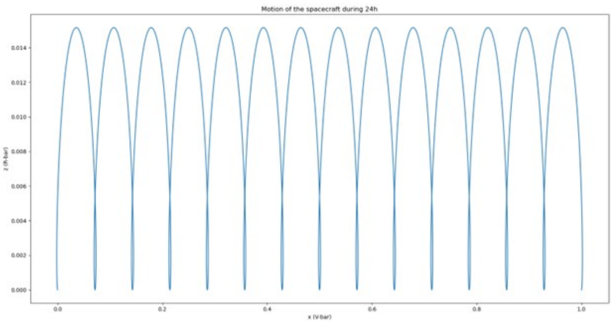

Figure 5: Motion of the spacecraft during 24 *hours* after the tangential maneuver

4 Propulsion System

In this chapter, it is discussed the selection and dimensioning of the propulsive system for Octopus. Its aims are to perform the Hohmann maneuver from the detachment from the launcher to the beginning of the rendezvous phase, to control the attachment on Zenit for the adhesion of the grippers, to perform attitude and control operations during the 10 years mission and to carry out the collision avoidance maneuvers.

4.1 Requirements and selection of the cold gas technology

From the functions that this system has to accomplish, the following requirements have been defined:

- A minimum of 10 collision avoidance maneuvers ($\Delta V = 4\ mm\ s^{-1}$) in 10 years time, using the thrusters in the Octopus legs.
- Δt = 15 min as the working time of the thrusters for the collision avoidance maneuvers.
- Operating temperature between 0°C and 50°C (thermal protection is needed and will be considered later).
- 10 years of propellant chemical stability.
- 20 % as the propellant mass margin.

4.2 Configuration

For the anticollision maneuvers, we have decided to involve only the thrusters in the legs of Octopus, after the deployment; in order to make sure to always have the good direction of the force and to be able to manipulate the debris in all the degrees of freedom around its axis, we have chosen to use three thrusters par leg. This redundant choice is made to

DOI: 10.13009/EUCASS2023-458

add safety to the system, knowing that adding cold gas thrusters have almost no influence on the final mass and configuration of the propulsive system, because of their low cost and small dimensions. The thrusters need to develop a force aligned with the tangential direction to the longitudinal axis of Zenit, as has been proved in the trajectory analysis.

Figure 6: Configuration of three thrusters par leg defined for Octopus

Globally, to perform the maneuvers, we can count on 12 thrusters of which 4 of them generates a force in the same verse and direction; in order to take into account the redundancy principle for safety reason, we accept that one of the aligned thrusters or legs is not working. Consequently, with only three thrusters we need to be able to develop a Δv = 4 $mm\ s^{-1}$.

4.3 System design and computation of the propellant mass

The propulsion system selected is derived from the Boeing Palomar Micro CubeSat Propulsion System, from VACCO.

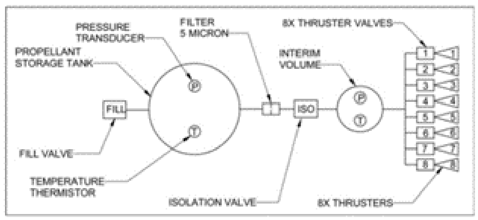

Figure 7: Flow schematic of the "classical" Palomar engine

The system is very simple: it only has a fill valve connected to the tank; the tank is self-pressurized, so there is no additional regulation system. In our case, instead of having an integrated model like the one proposed by the company. We will apply some modifications: we will have 12 thrusters instead of 8, which are not together with the tank and the propulsion assembly but are separated into groups of 3 and situated more than 3 meters away from the main body of Octopus. In addition, the dimensions of the tank will be different from the COTS component present in the market, but it will be again easily changeable.
From the datasheet, the specific impulse is known (I_{sp} = 59 s). Then, by taking into account the propellant density (Isobuthane, ρ = 563 kg m^{-3}), and the Tsiolkovsky equation ($\Delta v = I_{sp} \cdot g_0 \cdot ln(m_i/m_f)$), the propellant mass is (with the due additional margin of 20 %):

$$m_{p_{anticollision}} = 0.522\ kg \tag{11}$$

To complete the propulsion system for Octopus, we also need to consider the other maneuvers that our satellite needs to perform during the mission: the Hohmann maneuver, the Hopping maneuver and the attitude and control maneuvers. From the computation in the Trajectory and Attitude and Control paragraph, we can see that the contribution of the Hopping maneuver and the attitude and control is negligible if compared to the required Δv for the Hohmann maneuver, which is equal to 17 $m\ s^{-1}$. In this first phase of the mission, Octopus is still separated from Zenit, so we need to apply the required Δv only to our satellite (the estimated maximum mass of Octopus is around 25 kg). We will consider this additional need to size the final propulsive cold gas system, using Isobutane as the unique propellant and a central tank for these other functions. We also assume that we will have three little thrusters at each edge of the Nanotug to

DOI: 10.13009/EUCASS2023-458

correctly perform the Attitude and Control function: the scheme adopted is a well-known configuration.
The final specifications for the propulsive system are:

$$\begin{cases} m_{p_{tot}} = m_{p_{tot,main}} + m_{p_{anticollision}} = 1.307\ kg \\ V_{tank} = \dfrac{m_{p_{tot}}}{\rho_{isobuthane}} = 2.32\ L \end{cases} \tag{12}$$

This means that the central tank will be spheric, with a radius of 8.21 cm, which can be increased to 10 cm to have additional propellant and a safety margin. Globally, the propulsion system (thrusters, tanks and propellant) has a mass of around 10 kg.

5 Structure

Before starting any procedure to control the trajectory of the debris, Octopus needs to be physically attached to it. The high-level requirements imposed for the selection of the proper technology are the ability to stand an impact velocity at the end of the rendezvous phase up to 0.02 $m\ s^{-1}$, a lifetime of 10 years (minimum) and an operative range of temperature bigger than the one between 0 and 50 °C imposed by the type of propellant.

5.1 Physical Attachment to the debris

To find a proper solution, we have made a trade-off between different technologies: EA (Electrostatic Attraction or Electro Adhesion) grippers [5], FETCH (Flexible Electrostatic Tools for Capture Handling) and the innovative Gecko grippers [6] [7]. Based on this last technology, we selected the PSCU (Peeling-based Sandwiched Composite Unit) design in the configuration of a four-legged gripper, developed and tested by the State Key Laboratory of Tribology of Tsinghua University [8].
This configuration allows the attachment thanks to a self-adaptive-locking mechanism (SALM), that permits the system to handle cylindrical objects like Zenit with tangential adhesion. In addition, the system can easily support an impact velocity between 0.01 and 0.02 $m\ s^{-1}$ and their admitted range of temperature is between -50 °C and 50 °C, so they are compliant with the initial requirements. The gripping surfaces need to stay in contact with the debris for 30 seconds in order to establish adhesion: to do this, we need to use the springs contained in each leg. By considering four working thrusters of the propulsion system, the maximum continuous thrust is 0.035 N, so the needed stiffness amounts to 0.02 $N\ mm^{-1}$ for each spring. Instead, the preload spring is not necessary because we don't need to control any release once we are attached.
Octopus mass is negligible if compared to the debris; in a "zero gravity" environment, both forces and torques are not applied to the attachment. The only applied loads are due to the shear force generated by the thrusters during the anticollision maneuver and the effect of the movement of Zenit in its orbit. The computation made in the other paragraphs shows that no critical forces are generated and so the limits of the four-legged system, which can admit 260 N of normal force, 640 N of shear and 260 N m of moment, are compliant.
Finally, each leg has one gripping surface of 0.00084 m^2 at its ending with a thickness of 0.0082 m. Globally, the mass of the gripper is 0.412 kg. The resultant structure is small and just needs a contact surface of 60 mm x 60 mm to connect to the other structure and to be fixed on it.

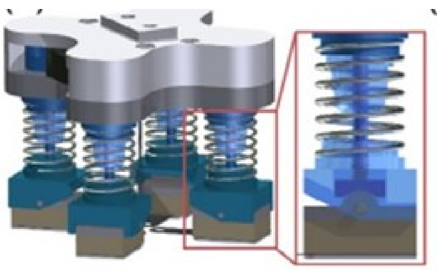

Figure 8: CAD model of the four-legged gripper [8]

DOI: 10.13009/EUCASS2023-458

5.2 Definition of the legs

After the attachment of Octopus to the debris, we need to deploy its legs. Four of these legs with more than one thruster each are needed in order to be able to command Zenit for the anticollision maneuvers. For the deployable structure, different solutions are possible, such as the neutrally stable [9] and the bistable tape springs [10], together with the CRTS (Collapsible Rib Tensioned Surface) reflector in the configuration of 6 ribs and a membrane as element of connection [11]. The choice is four parabolic mini-CTM booms: this solution has already been used in various past missions and it is more coherent with the main idea of the project to select COTS-derived components, readapted to the specific requirements. From the attitude and control analysis, Octopus has to stay at one-quarter of the length of the debris and the thrusters in all directions with respect to Zenit's stage to be able to control the movement of the body. For this reason, one leg is placed along each side of the structure, initially rolled up. At the end of each leg, the correspondent thrusters and antenna can be found, with a global external volume of around 5100 cm^3.

Each leg has the same length (3.5 m) so that no torque will be generated on the Octopus-Zenit assembly when the anticollision maneuver is performed. The force of 0.035 N/thruster is small if compared to the maximum load and moment that the booms can handle.
Each leg is attached to the structure in four separate contact points. The location of the connection is at one-sixth of the edge length from Zenit's surface side since during the deployment there will be a bending of the booms up to 12.5 mm in the maximum moment phase. The movement of the booms will end in 5 to 10 s time with the use of damping elements inside the stacking sequence of the laminate of the booms. To start the deployment, which is completely autonomous thanks to the bi-stability property of the booms, different options are possible: the use of classical mechanical springs, then released (as in the Space BEEs missions [12]), the use of an SMA wire applied on each leg and the use of the engine pressure to activate the movement.

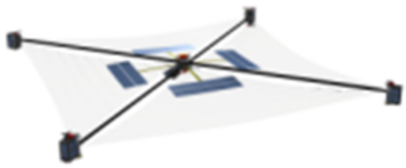

Figure 9: Example of deployed configuration with 4 legs [13]

In the latter solution, the propellant is sent through cables from the four tanks inside the NanoSat to the thrusters at the end of the legs. With the activation of this propulsive system, the propellant will start its movement and it will create a force on the boom. To activate the deployment, a small force of 0.29 N is required. In our case the force is more than the required:

$$F = p \times A = 43.85N \tag{13}$$

5.3 Global configuration and structure of Octopus

The global structure of Octopus is derived from a 6U CubeSat Aluminum structure, fabricated by ISISPACE. In our case, the final configuration will be modified in order to fit the mission requirements and host all the required components. In terms of dimensions, the biggest elements in Octopus are the propulsion system tank, the LIDAR and the magneto torquers. The tank occupies a volume of 0.00232 m^3, which corresponds to a spheric component with a radius of 0.0821 m, while the other two components are smaller, with a maximum dimension of 0.10 m. Globally the tank will take half of the total volume of the structure, which can be approximated as a cube with a side of 0.30 m.
The global mass of the structure is 4.5 kg.

DOI: 10.13009/EUCASS2023-458

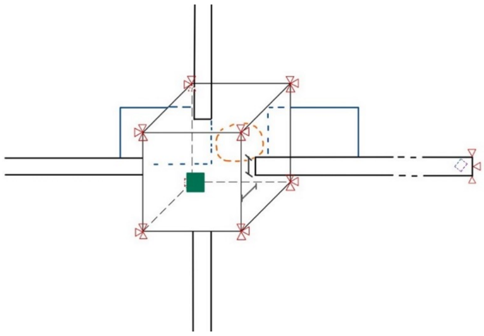

Figure 10: Final configuration of Octopus' structure and propulsion: the red triangles represent the thrusters, the blue parts are the solar panels, the orange circle is the main thruster, the green square is the Gecko's gripper and the four black rectangles are the legs

6 Navigation and Attitude Control

Regarding our mission, the satellite not only has to be able to keep its attitude (the FOV of the camera has to point the debris with an accuracy of 0.1 *deg*) during the continuous thrust maneuver (so that it can obtain all the information needed of the debris with cameras), it also has to be able to start moving accordingly to the debris (considering that the debris has a motion of maximum 2 *degrees* s^{-1} of tumbling). The camera and the onboard computer will be able to analyze the tumbling mode during the continuous thrust maneuver and depending on the mode of the tumbling of the debris (helicopter mode, bicycle mode, propeller mode) the octopus will star moving accordingly to the debris starting from 6 *meters* from the center of mass of the debris (considering the debris as a cylinder with a length of 10 *meters* and the center of mass and gravity exactly at the center of the cylinder) or starting from 3 *meters* (considering the debris as a cylinder with a radius equals to 2 *meters*), with an accuracy of 0.1 *deg* and 0.1 *deg* s^{-1}, in order to perform the adhesion.

6.0.1 Sensors

An accuracy of 0.1 *deg* and 0.1 *deg* s^{-1} must be provided, so it is not needed to use star trackers that would guarantee a higher accuracy but also a much higher cost. For this mission it's been decided to use a three axes magnetometer a minimum number of sun sensors and a three axes MEMS Gyro. This can be seen as a basic configuration for the orbital phase [2], starting from the launcher separation up to 1 km of distance from the debris and, during this phase, navigation will be done using GNSS.
The problem with the octopus is that the antenna could not be visible from the satellites. So, one solution would be to connect the legs of the octopus with a wire and have a GNSS antenna at the end of two legs of the octopus and one in the central body in order to be able to guarantee always a connection when needed. In this way the feet of the octopus will be able to exchange data with Earth and will communicate this data to the "head" of the octopus.

6.0.2 Detection of the debris

During the octopus' approach to the debris, it is necessary to have a good visualization of the debris, in order to visualize the way it moves and the distance from it. For this purpose, the octopus needs to have a camera and a laser in order to visualize the debris, determine the axis between octopus and debris, determine angles and to detect the distance from it.
Monocular cameras are considered as one of the most efficient solutions to obtain measurements for the onboard GNC chain and the results of the 2019 ESA's Kelvins Pose Estimation Challenge show that the most effective approach to deal with relative position and attitude estimation via monocular images is using CNNs aided PnP solvers [1].

For the detection of the surface of the debris it is decided to use a LIDAR and in order to be more accurate with the distance, it's needed to use also a laser range finder in order to have much more precision between the octopus' and the debris rendezvous. A disadvantage with the LIDAR is that it loses efficiency at about 30 *cm* from the target, so other solutions have to be explored (we will not talk about them in this report).

6.0.3 Attitude control system and detumbling maneuver

Concerning the attitude control, magneto torquers implemented with thrusters when needed will be used.
Once the octopus is attached to the debris, it is preferable to detumble the mode of the debris in order to perform the

DOI: 10.13009/EUCASS2023-458

just in time collision avoidance. It is possible to detumble the mode of the debris with thrusters or with the torqrods. Detumbling the mode with thrusters is the fastest possibility for sure, but it would imply a challenging use of propellant. On the other hand the attitude control implemented by torqrods is able to perform a detumbling maneuver without the use of additional propellant mass. Considering a magnetic moment of 50 Am^2 and a tumbling angular velocity of the debris of 2 $deg\ s^{-1}$, the detumbling maneuver can be done in approximately 23 $days$ without the use of additional propellant mass.

6.0.4 Conclusion

In conclusion, the AOCS of the presented mission is described by the following scheme:

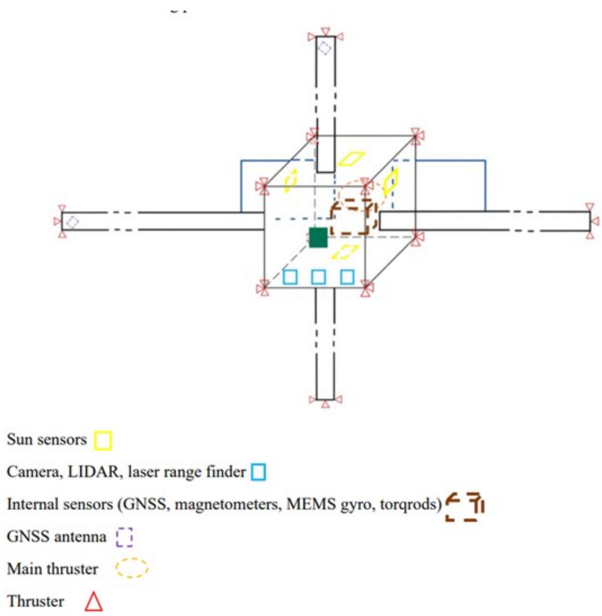

Figure 11: Draft of the design with the implemented attitude systems

7 Communication System

Regarding this chapter, some assumptions have been made:

- D = 2 m (geometric diamater of the antenna)
- f = 2.4 GHz (S-band frequency)
- Data rate = 1 kbps/30 dB (uplink) and kbps/40 dB (downlink)

7.1 Link Margin

The EIRP (Effective Isotropic Radiated Power) is estimated at 30 dB, considering the chosen components. Then, space losses, considering both the transmission losses and the ones due to the atmosphere are equivalent to 175 dB.
Using the assumed data rate (R), the system noise temperature (T_s) considered as 20 dB and the receiving antenna gain (G_r) equivalent to 35 dB, the ratio of received energy per bit to noise density $\frac{E_b}{N_0}$ is computed.

$$Link\ Margin = \frac{EIRP \cdot Losses \cdot G_r}{k_B \cdot T_s \cdot R} - \left(\frac{E_b}{N_0}\right)_{req} \tag{14}$$

By considering a bit error rate (BER) of 10^{-6} and 8-PSK modulation without coding, the link margin is closed in both uplink and downlink, with the worst case equivalent to 55 dB (uplink).

DOI: 10.13009/EUCASS2023-458

7.2 On Board Computer (OCB)

The major role of the OCB is to command the EPS (electrical power system) to disable or enable the different subsystems through various phases of the mission, and also receive, interpret, and execute commands from ground operators via the radio receiver. The choice is made upon the ISISPACE OBC, with a 32-bit, 400 MHz processor, a 3.3 V supply and a 400 mW power consumption.

7.3 Telemetry and Command

The remote interface unit implements functions related to the use of the sensors, such as temperature monitoring and control.
With the assigned orbit of 849 km and a simplified antenna elevation of 0° (it should be 5° at least), the visibility time stands at 952.4 s $\approx$ 16 min. In an optimistic case, the satellite can handle just under 9530 Mb in this time interval, using the S-band.

7.4 Sleep Mode

The sleep mode deals with the time interval between two avoidance maneuvers. Here, two orbits will be used as a backup for all the subsystems, and then the electrical/communication systems will switch to the reduced capacity, with just maintenance of the vital functions (housekeeping).

8 Thermal Control System

The TCS plays the fundamental role of keeping all the components within the operational range temperature. Within all the thermal requirements, two of them are the most concerning: the propulsion system one ([0°C 50°C] as operational and [-10°C, 60°C] as survival) and the transmitter ([-25°C 55°C] as operational and [-40°C, 70°C] as survival).

8.1 Thermal Loads

The external temperature is modelled as ranging between -60°C and 120°C, depending on the position in the orbit. Then, the internal temperature of the satellite is set at 20°C, while its dimension is taken as 0.4 m for each side of the cube.
Assuming also an emissivity of 0.9, the results are:

- Hot case: 125 W of absolute thermal load, or 840 $W\ m^{-2}$
- Cold case: -43.5 W of absolute thermal load, or -271.53 $W\ m^{-2}$

8.2 Insulations

A multi-Layer Insulation Blanket system (MLIB) has been chosen with the aim to change the effective emittance of the surface.

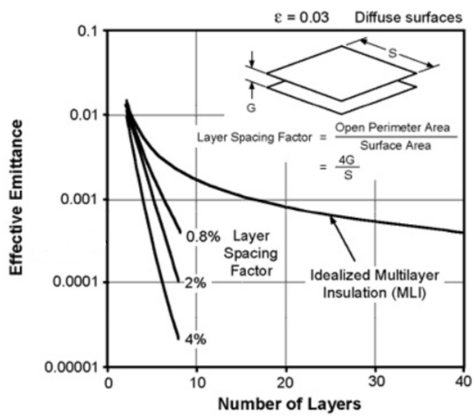

Figure 12: MLIB characteristics

DOI: 10.13009/EUCASS2023-458

In order to save space and weight, a 2% spacing factor is chosen, obtaining a 0.2 mm thick layer, with 10 layers. After this, specific internal insulation is needed for the propellant tank (-20°C for the isobutane). This component is specifically subjected to 10 W of thermal load, so 3 layers of insulation will be added. In the end, a flexible radiator foil is used for the electronic components.

9 Electrical Power System

Every subsystem presented up to this point has a specific power consumption. By adding all the needed power of each component, with its duty cycle, the final requested electrical power amounts to 31.179 W. To supply this request, solar panels and batteries will be sized in accordance with the power requirements.

9.1 Solar Panels

The solar panels sizing is based on the eclipse and sun time.

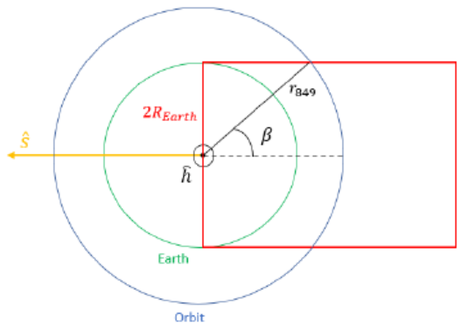

Figure 13: Reference frame for eclipse and sun time

Through geometric computations, $\beta = 1.08\ rad$ and:

$$T_{sun} = T_{orb} - \frac{T_{orb}\beta}{\pi} = 68\ min \tag{15}$$

Then, the required energies are computed, along with the power required by the solar panel P_{sp}.

$$\begin{cases} E_{sun} = P_{req} \cdot T_{sun} = 102000\ Ws \\ E_{ecl} = P_{req} \cdot T_{ecl} = 51000\ Ws \\ P_{sp} = \dfrac{E_{sun} + E_{ecl}}{T_{sun}} = 37.5\ W \end{cases} \tag{16}$$

The following values are assumed for the performances:

- Losses due to radiation damage of solar cells in LEO: $D_{LEO} = 0.62\%/year$
- Losses due to the temperature: $L_T \approx 0.9$
- Losses due to radiations: $L_D = (1 - D_{LEO})^{10yrs} = 0.94$
- Efficiency of the system: $\eta_{sys} = 0.85$
- Efficiency of the cells: $\eta_{cell} = 0.85$
- Filling factor: $\eta_{ff} = 0.85$

DOI: 10.13009/EUCASS2023-458

Assuming the solar flux corrected with the worst-case inclination of 45°, the area of the panel is:

$$A_{sp} = \frac{P_{sp}}{\Phi_{corr} L_T L_D \eta_{sys} \eta_{cell} \eta_{ff}} = 0.1504\ m^2 \tag{17}$$

9.2 Batteries

The assumption for the DOD (depth of discharge) is equal to 27 %. Then, the energy required by the batteries is:

$$E_{batt} = \frac{P_{req} \cdot T_{ecl}}{DOD} = 52.5\ Wh \tag{18}$$

The final configuration requires 3 batteries BA01/S High Energy Density LiPo Battery Array from the Ecuadorian Space Agency.

10 Cost and Mass Budget

Considering all the mentioned components for the design of the Octopus, an estimation of the cost and mass budget is given in the following table (launch, development, tests and qualification costs are not taken into account).
The reported values are not precise for every component, but they give us a general idea of the mean cost and mass expected, which are around 260,000 euros and 20 kilograms for one octopus.

Table 2: Component Mass and Cost

Component	Mass [kg]	Cost [euro]
Magnetometer	0.17	3,000
Sun sensor	0.016	10,000
Gyro	0.064	1,144
GNSS	0.06	7,400
Legs	1.5	80,000
Structure	3	20,000
Camera	0.040	4,890
Propulsive system	10	~50,000
Gecko's grippers	0.412	-
LIDAR	0.377	3,687
Laser rangefinder	0.033	6,000
Torqrod	1.44	40,000
Battery	0.345	13,200
Solar panel	~2	~4,000
Computer	0.1	5,000
Receiver	0.2	9,000
Total	**19.757**	**257,321**

11 Conclusions

This study designed a collision avoidance solution based on the JCA method.
Firstly, an upper stage of the Zenit-2 launcher has been selected as a representative target to compute the forces and torques required on this target to perform an avoidance maneuver. Then, a High-Level Requirements (HLR) document explains what our chaser will have to do as a final action.
Secondly, the chaser's injection orbit has been computed, and corrected to match the target's orbit before performing the rendezvous. Knowing the number of maneuvers to be carried out to be in the vicinity of the target, we calculated the total mass of propellant to carry on board and defined the best propulsion system.
Thirdly, comes the mean of attachment to the debris. Also it was necessary to define the number and the location of

DOI: 10.13009/EUCASS2023-458

the nano-tugs according to the target's movements. Now the "octopus" replaces the "swarm of Nano-Tugs" which interacts mechanically with the target, thanks to the Gecko technology. The octopus has a main body attached to the debris and four deployable "legs" which unfolds around the debris to drive its trajectory in the avoidance maneuver. The CubeSats are located at the ends of each "leg".
The next step, was the preliminary design of the CubeSat itself, aiming at something simple and cheap. Compromises between several major subsystems such as the propulsion, AOCS, rendezvous, TM-TC, thermal control and power distribution have been founded.
Finally, the study provided a simple cost and mass estimation for future commercialization.

References

[1] Michele Bechini, Paolo Lunghi, Michèle Lavagna, "Spacecraft Pose Estimation via Monocular Image Processing: Dataset Generation and Validation", 9 EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS), Under publication, Acta Astronautica 2023.

[2] Vincenzo Capuano, Cyril Botteron, Pierre André Farine, "GNSS BASED ATTITUDE DETERMINATION SYSTEMS FOR NANOSATELLITES", IAA-AAS-DyCoSS2-13-04, 2014.

[3] User's manual of Vega-C, Arianespace.

[4] Takahiro Sasaki, Yu Nakajima, Toru Yamamoto, "Proximity Approaches and Design Strategies for Non-Cooperative Rendezvous: V-bar Hopping vs. Spiral Approach", article in Transactions of the Japan Society for Aeronautical and Space Sciences , January 2021.

[5] Tom Bryan, Todd Macleod, Larry Gagliano, "Innovative Electrostatic Adhesion Technologies", 4th International Workshop on Space Debris Modelling and Remediation, 2016.

[6] Bo Zhu, Hao Cao, Zhouxiang Chen, Wentao Wang, Zhekun Shi, Kangjian Xiao, Yifeng Lei, Sheng Liu, Yi Song, Longjian Xue, "Bioinspired micropillar array with micropit for robust and strong adhesion", Chemical Engineering Journal, 2022.

[7] By Tony G. Chen, Abhishek Cauligi, Srinivasan A. Suresh, Marco Pavone, and Mark R. Cutkosky, "Testing Gecko-Inspired Adhesives With Astrobee Aboard the International Space Station", IEEE Robotics Automation Magazine, 2022.

[8] Xiaosong Li, Pengpeng Bai, Xinxin Li, Lvzhou Li, Yuanzhe Li, Hongyu Lu, Liran Ma, Yonggang Meng, Yu Tian, "Robust scalable reversible strong adhesion by gecko-inspired composite design", Friction 10, 2021.

[9] Marc R. Schultz, Michael J. Hulse, Philip N. Keller, Dana Turse, "Neutrally stable behaviour in fiber-reinforced composite tape springs", ScienceDirect Volume 167, 2008.

[10] Andrew J. Lee, Juan M. Fernandez, Jacob G. Daye, "Bistable Deployable Composite Booms With Parabolic Cross-Sections", AIAA SCITECH 2022 Forum, San Diego, 2022.

[11] S. Pellegrino, "CRTS REFLECTORS", Department of Engineering, University of Cambridge Trumpington Street, Cambridge, 2002.

[12] Krebs, Gunter D., "SpaceBEE 1, 2, 3, 4", Gunter's Space Page, 2018.

[13] Marco Straubel, Cristian Hühne, "CTM Boom deployment mechanism with integrated boom root deployment for increased stiffness of the boom-to-spacecraft interface", European Conference on Spacecraft Structures, Materials and Environmental Testing, 2021.